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MECHANICAL, CORROSION, AND FATIGUE PROPERTIES OF 15-5 PH, INCONEL 718, AND RENÉ 41 WELDMENTS

by

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Weldments of three hydrofoil strut/foil candidate materials (15-5 PH stainless steel, Inconel 718, and René 41) for hydrofoils were prepared. Mechanical, fatigue, corrosion fatigue, and corrosion tests were performed on these materials with various postweld heat treatments. Results of tensile, impact,

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fatigue, stress corrosion, general corrosion, and crevice corrosion tests are presented. Weld procedures, problems, and machining difficulties are noted. The corrosion properties of René 41 and Inconel 718 are superior to 15-5 PH stainless steel; however difficulty in welding and machining these nickel-base alloys in thick sections make their application to hydrofoils highly unlikely without further development. Although not performing as well in seawater as the other two alloys, 15-5 PH is considerably easier to fabricate and therefore warrants consideration for hydrofoil struts and foils.

(Author)

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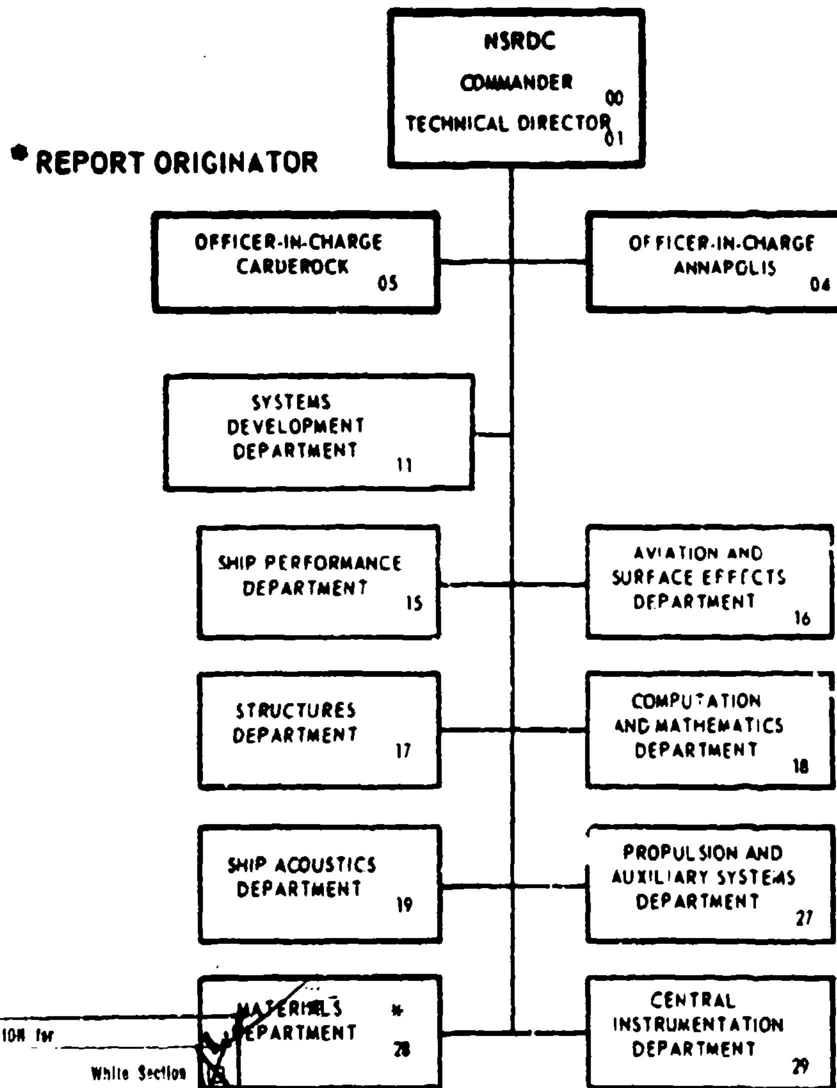

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ADMINISTRATIVE INFORMATION

This is a summary of work conducted under Task Area S4606, Task 01724, on Hydrofoil Materials, Work Unit 1153-003.

LIST OF ABBREVIATIONS

cpm	-	cycles per minute
cu ft/hr	-	cubic feet per hour
° F	-	degrees Fahrenheit
ft-lb	-	foot-pound
hr	-	hour
in.	-	inch
in/hr	-	inches per hour
in/min	-	inches per minute
ksi	-	thousand pounds per square inch
min	-	minute
No.	-	number
psi	-	pounds per square inch

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INTRODUCTION

Struts and foils of Navy hydrofoil craft are presently constructed of various high-strength steels, stainless steels, or aluminum alloys. These low alloy steels and aluminum alloys require coatings for corrosion protection. There is a need for pertinent data on a wider selection of alloys, particularly nickel-base alloys, for future selection of strut and foil materials. Niederberger, et al,[1] have investigated the performance of 22 nickel alloys in quiet seawater. Three alloys exhibited no general corrosion, pitting, or crevice attack, but only one, René 41, was of sufficiently high strength to be attractive for hydrofoil use. Those alloys which were susceptible to moderate crevice corrosion included only one material desirable for struts and foils, Inconel 718.

Precipitation-hardenable stainless steels have been used with success in hydrofoil craft. Most experience has been obtained with 17-4 PH, which is subject to crevice corrosion and has nonuniform properties in large section sizes. The alloy has been replaced in certain commercial applications by 15-5 PH, which is similar in composition. Although both alloys can be made by either air or vacuum melting, the 15-5 PH grade appears to be the more readily available alloy in vacuum-melted form. It was included in this investigation because of possible future use in hydrofoils.

The purpose of this investigation is to evaluate weldments of three alloys, René 41, Inconel 718, and 15-5 PH stainless steel, for possible hydrofoil applications. A brief description and history of each alloy is provided, along with mechanical, seawater corrosion, and corrosion fatigue data for welded plate in various heat treatments. This is a final report containing a summary of information previously presented, as well as new information.

[1] Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

BACKGROUND

15-5 PH STAINLESS STEEL

A precipitation-hardenable martensitic stainless steel, 15-5 PH is similar in composition and properties to 17-4 PH stainless steel, which was used as strut and foil material on the USS TUCUMCARI (PGH 2). It was originally developed for high-temperature use by Armco Steel Corporation.[2] High strength is obtained by the precipitation of compounds of copper, columbium, and tantalum in a matrix high in chromium and nickel. This 15-5 PH alloy has generally better properties than 17-4 PH, due to the elimination of a delta-ferrite phase.[3] Like its predecessor, 17-4 PH, 15-5 PH is subject to crevice corrosion, although perhaps not as severely, as it is reported to exhibit superior resistance in laboratory tests in salt fo and chloride pitting solutions.[3]

Welding of 15-5 PH is similar to that of 17-4 PH and has been well documented. Usually, 17-4 PH welding wire is used. Heat treatment consists of a solution anneal at 1900° F,* followed by aging at 900° to 1400° F, depending on desired properties.[4]

Alloy 15-5 PH has been used in several applications in lieu of 17-4 PH, where better transverse properties, better impact properties, or larger section sizes are required. For these reasons it has been used successfully in gas turbines in aircraft. Due to its similarity to 17-4 PH and its reported uniformity of properties in larger section sizes, this alloy was considered to be a good candidate to succeed 17-4 PH as a strut and foil material.

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*A list of abbreviations used in this text appears on page i

RENE 41

René 41 was developed by General Electric Company as a high-temperature turbine alloy. It is a nickel-base alloy, high in chromium, cobalt, and molybdenum. Its high strength comes from the precipitation of a gamma-prime phase consisting of Ni_3Al and Ni_3Ti, and from the solid solution effects of chromium and molybdenum. The cobalt addition retards recrystallization. Heat treatment usually consists of solution annealing at 1975° to 2150° F, followed by water quenching, and aging at 1400° to 1800° F to precipitate the coherent ordered face-centered-cubic, gamma-prime compounds.[5]

Unfortunately, the rapid precipitation of gamma prime in this alloy creates severe welding problems, such as microfissuring and strain-age cracking. Strain-age cracking occurs upon heating the metal after welding. Between 1400° and 1650° F as the precipitation reaction begins, the metal ductility is severely reduced.[6] Grain boundaries are weakened by adsorption of oxygen.[7] Maximum thermal stress also occurs at these temperatures. This combination of factors may result in severe cracking in metal when residual stresses are present. The cracking can be minimized by overaging the base plate before welding, giving a ductile base material to absorb much of the residual stress,[6] or by postweld heat treatment in vacuum or an inert atmosphere, such as argon, to eliminate oxygen embrittlement.

Microfissuring, due to partial liquefaction of the metal during welding, occurs mainly at the weld root where shrinkage stresses are encountered.[6] This may be avoided by using a more ductile material, such as Hastelloy W, for the root passes, a procedure which slightly lowers joint efficiency. (Joint efficiency is the ratio of the tensile strengths of welded to unwelded material.)

René 41 has been used successfully for critical aircraft and rocket components subjected to high temperatures, such as after-burner parts, nozzle partitions, turbines, and structural hardware.[1] Strain-age cracking and microfissures have, however, been found occasionally in various welded components.[1,6] The primary research for better welding techniques to eliminate these problems has been carried out by General Electric Company and Rocketdyne Division of North American Aviation, mostly on sheet and plate up to 3/8 inch thick. Only recently were the good seawater corrosion properties of this alloy recognized and the material considered for high-strength marine applications.

INCONEL 718

Inconel 718 was developed by the International Nickel Company originally for high-temperature turbine use. Like René 41, it is a nickel-base alloy high in chromium, cobalt, and molybdenum, with strengthening by a gamma-prime coherent precipitate. However, the gamma prime consists of Ni_3Cb, which precipitates much more slowly than the Ni_3Al and Ni_3Ti compounds in René 41. This considerably reduces the problem of strain-age cracking, since residual stresses can be relieved before the onset of the precipitation reaction.[11] Heat treatment usually consists of solution annealing at 1700° to 1850° F, followed by aging at 1150° to 1325° F; or annealing at 1900° to 1950° F, followed by aging at 1200° to 1400° F, depending on the properties desired.[12]

Welding of Inconel 718 is easier than René 41, due to a lesser tendency towards microfissuring and strain-age cracking. Gas-tungsten-arc (GTA) welding methods have been well documented, while gas-metal-arc (GMA) welds have met with only moderate success.[11,13] Considerable welding research has been done on this alloy by the industry.[11] As a result of this research, Inconel 718 has seen considerable use in high-temperature applications in aircraft and rockets. Its resistance to sea-water has also been documented,[1] and, although its use for hydrofoil craft has been considered before, corrosion fatigue tests of weldments have not been performed.

MATERIAL, WELDING AND HEAT TREATMENT

15-5 PH STAINLESS STEEL

One annealed bar of 15-5 PH stainless steel, 1 1/2 x 5 x 144 inches was obtained from Armco Steel. This bar was subsequently cut into four 36-inch-long pieces for welding. Four 25-pound spools of 0.045-inch-diameter 17-4 PH stainless-steel wire were obtained for welding from National Standard Company. Chemical compositions of these materials are given in table 1.

TABLE 1

CHEMICAL COMPOSITIONS OF STAINLESS STEEL

Chemical Composition	Material 15-5 PH Bar Heat 1W0516	17-4 PH Wire Heat 602575
Cr	14.69	16.41
Ni	4.61	4.83
Cu	3.21	3.62
Cb	0.21	0.28
C	0.020	0.040
Mn	0.16	0.56
P	0.015	0.016
S	0.011	0.019
Si	0.35	0.50
Ta	0.01	0.01
Fe	Remainder	Remainder

Figure 1 shows the sequence of welding and heat treating of the 15-5 PH bars. Two 36-inch weldments were made, one of which was subsequently reannealed at 1900° F for 1 1/2 hours and aged at 1075° F for 4 hours, and cut into blanks. Base metal blanks were machined into tensile and impact specimens. Welded blanks were machined into tensile, impact, and smooth fatigue specimens, three types of corrosion specimens, and side bends.

Welding was performed with an automatic GTA apparatus by the Youngstown Welding and Engineering Company. The optimum weld joint geometry for this material was found to be a double "U" groove type, as illustrated in figure 2. Filler wire was 17-4 PH stainless steel. Weld parameters also appear in figure 2.

Two passes were first put on one side. The opposite side was then back-ground to sound metal, and after dye-penetrant inspection was performed, two more passes were put in. One weld exhibited cracklike indications which were then removed, and the weld was inspected with dye penetrant and X-rays. Because no indications of cracking were seen, two more passes were placed on this side. Subsequently, passes were completed in sets of four, on alternating sides, until there were 60 passes on one side and 62 on the other.

The second welded plate, after back-grinding, had four passes welded before it was X-rayed for defects. Because the X-rays were clear, the plate was turned and eight passes welded. Passes were then completed in sets of four, alternating sides, until one side had 55 and the other 59.

Both plates were X-rayed after welding and dye-penetrant inspection was performed. One X-ray showed 2 to 4 inches of longitudinal weld cracks, while the other was clear. The plate showing the clear X-ray was selected for testing.

INCONEL 718

Four hot-rolled and annealed Inconel 718 plates were obtained from Huntington Alloy Products Division of the International Nickel Company, Incorporated. Two plates were 1 x 6 x 48 inches and two were 1 x 6 x 72 inches. The latter plates were cut to give four pieces 1 x 6 x 36 inches. Three 25-pound spools of 0.045-inch-diameter Inconel 718 welding wire were also obtained from the International Nickel Company. The chemical compositions of these materials appear in table 2.

Figure 3 shows the sequence of welding and heat treating of the plates. The 36-inch plates were aged before welding and the 48-inch plates after welding. Aging before welding simulates the condition of repair welds, while postweld aging simulates a heat-treated fabricated structure.

Welding was performed with an automatic GTA apparatus by the Youngstown Welding and Engineering Company. The optimum weld joint geometry for this material was found to be a single "U" groove and the filler wire was Inconel 718. The weld parameters are listed, and a drawing of the welding setup appears in figure 4.

TABLE 2

CHEMICAL COMPOSITIONS OF INCONEL 718

Chemical Composition	Material	
	Inconel 718 Plate Heat HT83C2EK	Inconel 718 Wire Heat HT5[illegible]BOE
Ni	53.69	54.58
Cr	18.55	17.91
Fe	17.37	17.60
Ta	5.23	0.01
Mo	2.93	2.96
Ti	0.98	0.99
Al	0.68	0.49
Si	0.20	0.19
Cu	0.13	0.05
Mn	0.12	0.04
C	0.06	0.04
Co	0.03	0.04
S	0.007	0.007
P	0.006	0.011
B	0.0029	0.0031

A reinforcement pass was first made on the back of the land. The plates were then reversed and the remaining land was back-ground until dye-penetrant inspection revealed no areas where weld metal had not penetrated. Two passes were then laid in the weld root. A 1/8-inch bow was then put in the plates in the welding fixture and the root was then X-rayed to ensure that no porosity or cracks existed. All three welded plates were found to be sound. The plates were then welded approximately 1/3 of the way up until they straightened out due to the shrinkage of the weld metal upon solidification. They were again mechanically bowed back 1/4 inch and X-rayed. Indications of linear cracking appeared in the 48-inch-long weld. These were ground out and inspected by dye-penetrant. The two 36-inch welds appeared sound. The remaining passes were completed and the plates flattened. The final welds were X-rayed. It was noted that the longer weld contained longitudinal cracks about 6 inches long while the shorter welds appeared sound. Approximately 75 to 80 passes were used on each weld.

RENÉ 41

One plate of René 41, hot-rolled, pickled, and annealed, 1 x 36 x 48 inches, was obtained from Union Carbide Corporation Two 25-pound spools of 1/16-inch-diameter bare drawn René 41 weld wire were also obtained from this source. The chemical compositions of these materials are given in table 3.

TABLE 3
CHEMICAL COMPOSITIONS OF RENÉ 41

Chemical Composition	Plate Heat 2490-0-8147	Wire Heat 2490-8-8142
Cr	18.36	18.78
Mo	9.70	9.83
Fe	3.15	0.97
C	0.11	0.09
Si	0.16	0.10
S	0.007	0.002
Mn	0.01	<0.01
B	0.006	0.005
Al	1.53	1.45
Ti	3.11	3.16
P	-	-
V	-	-
Co	11.26	11.11
Ni	Remainder	Remainder

All plates of René 41 were originally overaged by the heat treatment, 1975° F for 1/2 hour, furnace cooled at 50° F per hour. The sequence for welding and subsequent heat treating the René 41 plate is shown in figure 5. Postweld reannealing was done in an inert atmosphere to reduce the tendency for strain-age cracking. In order to heat the welds quickly through the critical range of temperatures to avoid cracking, a higher annealing temperature was used.

Welding was performed at this laboratory with an automatic GTA apparatus. The optimum weld joint geometry for this material was found to be a double "V" configuration. The weld parameters and weld joint geometry appear in figure 6. After the root passes were placed on one side, the plates were back-ground to eliminate root cracking where penetration of the weld metal was difficult. Dye-penetrant inspection was performed after grinding to ensure complete removal of any cracks. Welding was then completed, alternating sides after each group of several passes to minimize distortion.

Dye-penetrant and radiographic inspections were performed after welding. While one weld showed no indications of cracks, X-rays of the other indicated about 6 inches of cracking in the root.

EXPERIMENTAL PROCEDURES

TENSILE TESTS

Duplicate standard 0.505-inch-diameter tensile specimens were tested for each base material in each heat treatment. 15-5 PH and Inconel 718 transverse-weld specimens were tested in each heat treatment. The strain rate was 0.002 in./in./min up to the point of yielding.

CHARPY V-NOTCH IMPACT TESTS

Triplicate Charpy V-notch specimens were tested for each base material in each heat treatment. 15-5 PH and Inconel 718 transverse-weld specimens were tested in each heat treatment at room temperature and at -80° F.

DYNAMIC TEAR IMPACT TESTS

Triplicate 5/8-inch dynamic tear impact specimens were tested for each base material in each heat treatment. 15-5 PH and Inconel 718 transverse-weld specimens were tested at room temperature and at -80° F.

FATIGUE TESTS

Ten smooth specimens were taken from welded plates of Inconel 718 in both heat treatments and 15-5 PH which had been postweld aged. Half were run in air and half in Severn River water. All specimens were run at a frequency of 1450 cpm in fully reversed bending.

GENERAL CORROSION TESTS

Duplicate panels, 1/4 x 3 x 10 to 12 inches, were cut from welded plates of each material and heat treatment and were exposed in natural seawater for 1 year at the Francis L. LaQue Corrosion Laboratory, Wrightsville Beach, North Carolina.

CREVICE-CORROSION TESTS

Duplicate panels, 1/4 x 3 x 10 to 12 inches, were cut from welded plates of each material and heat treatment. A crevice was created in the center of each panel by affixing a 1-inch-square piece of matching material on one side and a 1-inch square of nylon on the other. Both crevice pieces were held in place by the same nylon nut and bolt. These specimens were exposed in natural seawater for 1 year.

STRESS-CORROSION TESTS

Two bent-beam stress-corrosion specimens were taken from welded plates of each material and heat treatment. One was stressed to 50% of the yield strength and the other to 90% of the yield strength. These specimens were exposed in natural seawater for 1 year. In addition, modified wedge-opening-loading (WOL) fracture specimens were employed to determine the values of K_{IC} and K_{ISCC} for René 41 base metal.

METALLOGRAPHY

Metallographic specimen preparation was accomplished by grinding through 600-grit paper and polishing with 0.3- and 0.05- micron diamond paste. The nickel-base alloys were then etched for a minimum of 30 seconds with aqua regia; 80% HCl, 20% HNO_3. The stainless-steel specimens were etched for about 10 seconds in Fry's reagent. Macrophotographs of the welds and 50X microphotographs of the weld root were then taken.

RESULTS AND DISCUSSION

15-5 PH STAINLESS STEEL

Results of the tensile and impact tests on 15-5 PH stainless steel are presented in table 4. The data indicate that postweld reannealed and aged 15-5 PH performs as well as base material except in impact. As-welded material exhibited lower elongations, reduction of areas, and impact properties than

postweld reannealed and reaged material, although the reduction of area value was still similar to that of the base metal. **Tensile failures of as-welded material generally occurred in the weld.**

TABLE 4
MECHANICAL PROPERTIES OF 15-5 PH STAINLESS STEEL

	Base Plate				Welded (On Annealed Base Plate)	
	Mill Annealed		Aged 1075° F		As-Welded, Transverse	Postweld Reannealed 1900° F and Aged 1075° F, Transverse
	Transverse	Longitudinal	Transverse	Longitudinal		
Yield strength, ksi		122	150	149	-	-
Tensile strength, ksi		156	156	153	156	155
Elongation, %		19	15	19	11	17
Reduction of area, %		63	48	62	49	54
Charpy V-notch energy, ft-lb						
RT	33		42	67	19	40
-80° F	28		23	26	11	17
5/8-Inch DT energy, ft-lb						
RT		613		583	213	293
-80° F		490		113	97	113

RT - Room temperature.
DT - Dynamic tear.

Results of the fatigue and corrosion fatigue tests on 15-5 PH are presented in figure 7. The endurance limits for welded material in air and in Severn River water are 43 and 29 ksi, respectively.

Results of all the general corrosion tests indicate that although only small surface pits may be visible, they frequently did not indicate the true extent of subsurface corrosion attack as revealed by radiographic techniques. As-welded general corrosion panels displayed behavior suggestive of HAZ corrosion under certain conditions. One specimen displayed intense corrosion initiating at the edge of the low-temperature side of the weld HAZ area. It extended approximately 3/4 inch along

the HAZ and resulted in complete penetration of the 1/4-inch panel. Attack was so well defined that the angle of the weld edge could be accurately determined. Intense localized insidious pitting/tunneling occurred in the base plate parallel to, and about 1 1/4 inch away from, the weld. The duplicate specimen displayed no attack in or around the weld area but did show severe localized pitting/tunneling attack in an area parallel to, and approximately 1 1/4 to 2 inches away from, the weld.

As-welded crevice-corrosion panels experienced dramatic classical intense knife-edge attack in the low-temperature side of the weld HAZ, as illustrated in figure 8. In both specimens the attack under the 1-inch-square crevice areas produced by the washers was about 1/32 inch wide, completely penetrating the specimen and clearly following the angle of the weld edge. Knife-edge tunneling initiated at the crevice and extended up to 3/8 inch along the HAZ outside of the crevice area beneath the surface. Preferential attack of the base metal beneath the crevice was also observed.

One as-welded stress-corrosion-cracking (SCC) panel developed intense crevice corrosion at the ends in contact with the stressing fixture, causing unloading and invalidating the stress-corrosion portion of the test. This specimen displayed insidious pitting/tunneling corrosion but experienced no preferential attack at or around the weld. The second specimen experienced no appreciable crevice attack at the fixture, but still was subject to insidious pitting/tunneling. In addition, knife-edge attack was seen on the second specimen in the low-temperature HAZ area, as shown in figure 9, clearly outlining the weld for a short distance before being overridden by the tunneling attack. It is difficult to tell from outward appearance if this knife-edge attack was due solely to preferential attack of a sensitized region or whether stresses in the specimen were also a contributing factor. Figure 10 shows a posible cause of this attack. The upper section of this figure pictures the microstructure of the as-weld specimens. The knife-edge attack occurred at the low-temperature edge of the heat-affected zone. The micrograph shows a dark phase located precisely in the area of the attack which may be a contributing factor.

Four high-magnification scanning electron photomicrographs of selected areas of the microstructure compose the lower portion of figure 10. The left-hand photo shows the fine dendritic structure existing in the weld metal. The next photo shows a fine, equiaxed structure with acicular regions existing in the middle temperature heat-affected zone, resulting from the heat of welding. Between these two areas is a region within the high-temperature, heat-affected zone where partial liquification probably has occurred, causing distinct outlining of the grain boundaries. The right-hand photo shows the coarse structure of the base metal. Next to this is a photo of the region where the dark phase corresponding to the area of knife-edge attack occurs. This structure shows that the precipitates had a preferred orientation. The prior grain boundaries are also evident. Unfortunately, further analysis of this structure is not practical due to the narrow width of the zone where it exists.

None of the re-heat-treated specimens experienced preferential attack at the weld or HAZ areas. All specimens were subject to catastrophic pitting/tunneling attack which in some cases completely removed up to 2 square inches of the 1/4-inch panels. In addition, extensive crevice corrosion was present under the 1-inch-square washers on the crevice panels. The stress-corrosion tests were invalidated due to specimen relaxation caused by crevice corrosion at the specimen ends contacting the stressing fixture. Under the crevice pieces, the base metal was attacked somewhat preferentially to the weld metal.

INCONEL 718

Results of the tensile and impact tests on Inconel 718 are presented in table 5. The data indicate that welded material exhibits a 25% reduction in yield strength and elongation compared to aged base plate. The impact properties of the welded plates are however, higher. Tensile failures were in the weld. Postweld aging, although improving the tensile strength, causes severe reductions in ductility and impact properties.

The heat created during the welding of aged Inconel 718 by the large number of passes, partially ages the previously laid beads, improving their strength. The mechanical properties of this weld, with its higher strength than annealed plate, and better ductility than overaged plate, are desirable for repair welding considerations without postweld heat treatments. Aging after welding gives higher strengths and lower ductilities than welding aged plate with no subsequent heat treatments.

TABLE 5
MECHANICAL PROPERTIES OF INCONEL 718

	Base Metal				Welded (On Annealed Base Plate)	
	Mill Annealed		Aged 1325°-1150°F		Preweld	Postweld
	Transverse	Longitudinal	Transverse	Longitudinal	Aged 1325°-1150° F Transverse	Aged 1325°-1150° F Transverse
Yield strength, ksi	-	59	152	155	-	-
Tensile strength, ksi	-	125	186	194	141	182
Elongation, %	-	40	11	15	8	4
Reduction of area, %	-	52	14	17	25	4
Charpy V-notch energy, ft-lb						
RT	46	-	14	22	32	9
-80° F	41	-	11	18	25	6
5/8-Inch DT energy, ft-lb						
RT	-	577	-	172	195	80

Results of the fatigue and corrosion fatigue tests are presented in figure 11. Data for both heat treatment conditions, preweld or postweld aging, in air and in Severn River water, all fell within the same scatter band with a lower limit of 29 ksi.

Inconel 718 experienced no general corrosion and only minor and very scattered pitting, possibly due to crevices under marine organisms. HAZ corrosion was present, initiating only at severe crevices. The material in all heat treatments did, however, experience extensive crevice corrosion, primarily under crevice washers and holding fixtures. Stress-corrosion data was not possible to obtain due to specimen stress relaxation caused by corrosion at the fixture.

No significant problems were encountered during welding of Inconel 718 even in the aged condition. Inert atmosphere heat treatments were not necessary and strain-age cracking was not present. The data indicate that if microfissuring were present, it has an insignificant effect on mechanical properties.

Unfortunately, because this material work hardens rapidly, thick sections were extremely difficult to saw, even when overaged. Sawing speeds were about 4 in/hr on the 1-inch plate when carbide-tipped blades are used, compared with 12-16 in/hr for HY-130 steel. Speeds were improved using a carbide wheel, up to 20-25 in/hr. Drilling likewise required care and the use of a sharp, carbide-tipped drill was mandatory.

RENÉ 41

Results of the tensile and impact tests for René 41 base metal are presented in table 6. Data could not be obtained for welded material, because of the difficulty of producing sound welds, as explained in Appendix A. As expected, aged base plate is stronger and less ductile than overaged base plate. Elongation and reduction in area are approximately equal, indicating rapid work hardening. This is supported by the absence of significant necking in the test specimens. Differences in Charpy energies between room temperature and -80° F are slight, indicating no ductile-brittle tranformation in this range.

TABLE 6

MECHANICAL PROPERTIES OF RENÉ 41 BASE METAL

	Overaged 1975° F	Annealed 2150° F and Aged 1400° F
Yield strength, ksi	92	12[illegible]
Tensile strength, ksi	165	178
Elongation, %	2[illegible]	16
Reduction of area, %	19	15
Charpy V-notch energy, ft-lb		
RT	24	11
-80° F	21	[illegible]

Welded René 41 experienced no corrosion attack of any kind in seawater. All surfaces still had machining marks and were bright after 1-year exposures. No stress-corrosion failures were observed. Two modified WOL fracture specimens, loaded to 59.5 and 77.6 ksi $\sqrt{in.}$ showed no crack extension after 1 year in seawater. The final values after exposure were 55.5 and 70.1 ksi $\sqrt{in.}$ due to the wedging effect of corrosion products from the loading bolt. Therefore, the K_{ISCC} value for this material is greater than 77.6 ksi $\sqrt{in.}$ The air value of K_Q (the invalid K_{IC} value) determined from the third specimen was 86.6 ksi $\sqrt{in.}$

A disadvantage of René 41 is its poor machinability in thick sections. Sawing and drilling were even more difficult than Inconel 718, due to the high work-hardening coefficient of the material. Grinding did not appear to be exceptionally difficult, however.

CONCLUSIONS AND RECOMMENDATIONS

The corrosion properties of René 41 are extremely desirable, as this material appears to be immune to attack in seawater. Inconel 718 has corrosion properties slightly superior to 15-5 PH and a corrosion fatigue strength which is equivalent. However, neither René 41 or Inconel 718 is recommended for hydrofoil strut/foil applications in their present stage of development, due to their difficulty of fabrication. Struts and foils consist of many elaborately machined sections held together by a variety of weld configurations. As machining and welding of thick sections of these nickel-base alloys are very difficult, these materials should not be used on hydrofoils without further investigation of their machinability and weldability.

Although not performing as well in seawater corrosion as the other two alloys, 15-5 PH stainless steel is considerably easier to fabricate and therefore warrants consideration for hydrofoil struts and foils. The crevice corrosion seen on the test specimens should not be a problem on retractable foil designs. However, the HAZ attack could present problems in the use of this material. Additional research is needed to determine whether this problem can be eliminated by the use of low-temperature heat treatments or by compositional control.

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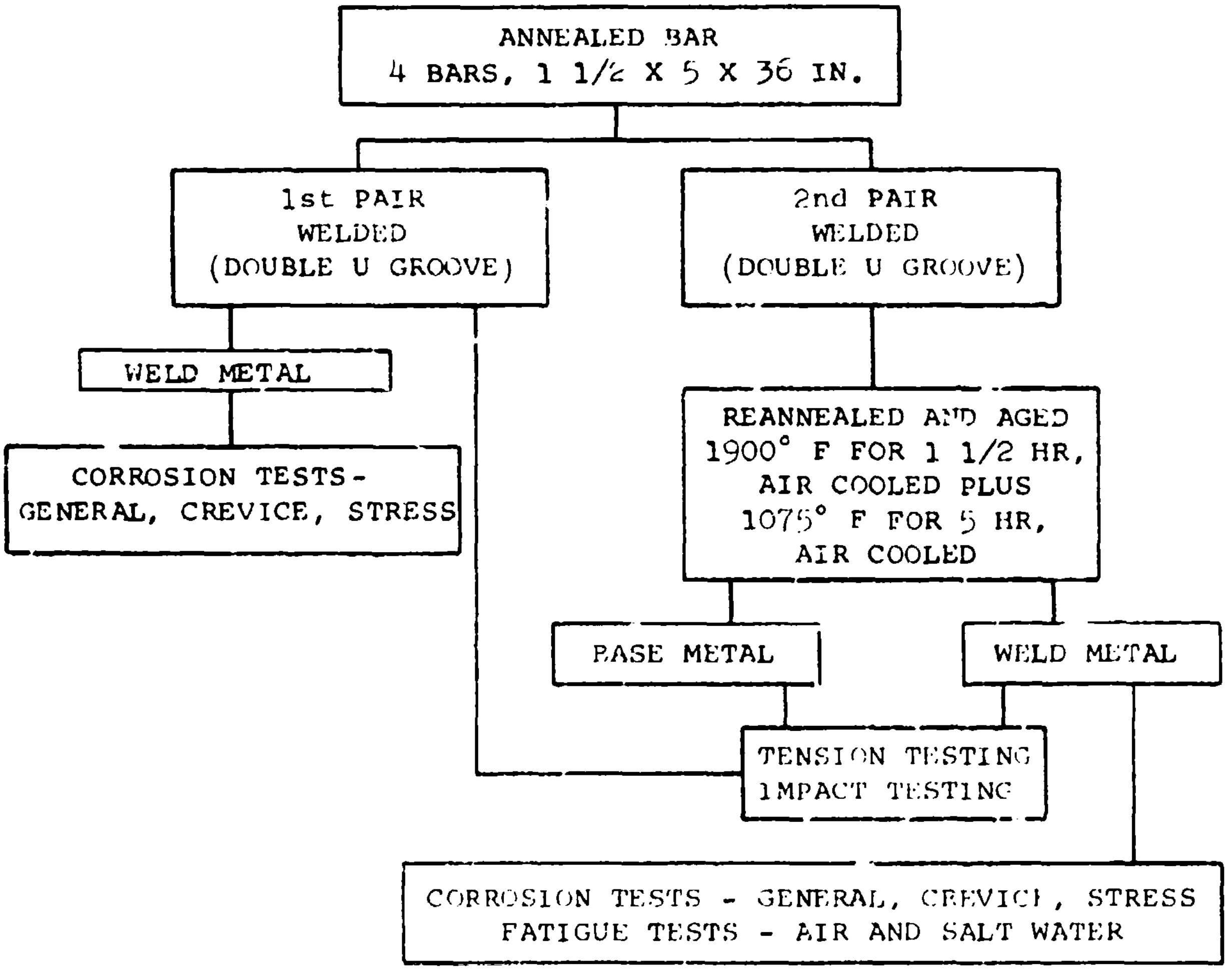
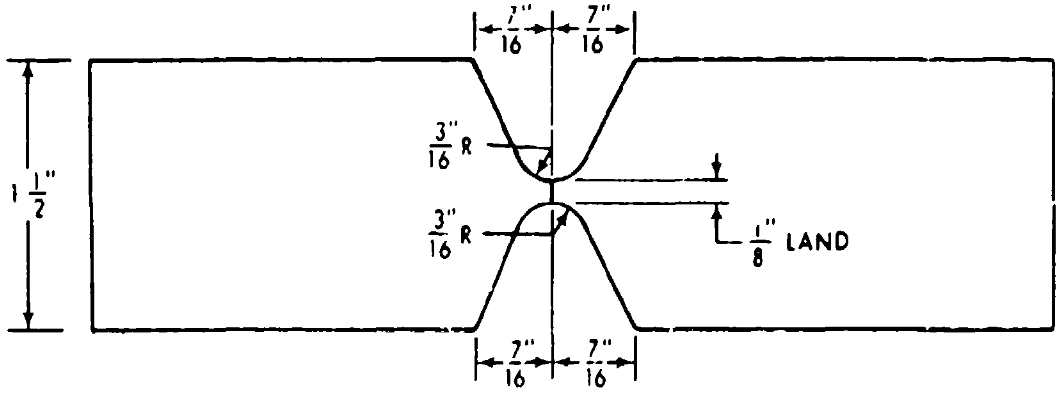


Figure 1
Welding and Heat Treatments
15-5 PH Stainless Steel

4528

Arc Voltage	- 10-12
Arc Current, amperes	- 175-225
Travel Speed, in/min	- 12
Wire Feed, in/min	- 30-52
Interpass Temperature, ° F	- 150 Maximum
Gas, cu ft/hr	
Torch	
Helium	- 35
Argon	- 12
Trailing Shield	
Argon	- 30
Back Shield	
Argon	- 10
No. of Passes	
First Weld	
Top	- 60
Bottom	- 62
Second Weld	
Top	- 55
Bottom	- 59



WELD JOINT

Figure 2
Welding Parameters
15-5 PH Stainless Steel

4528

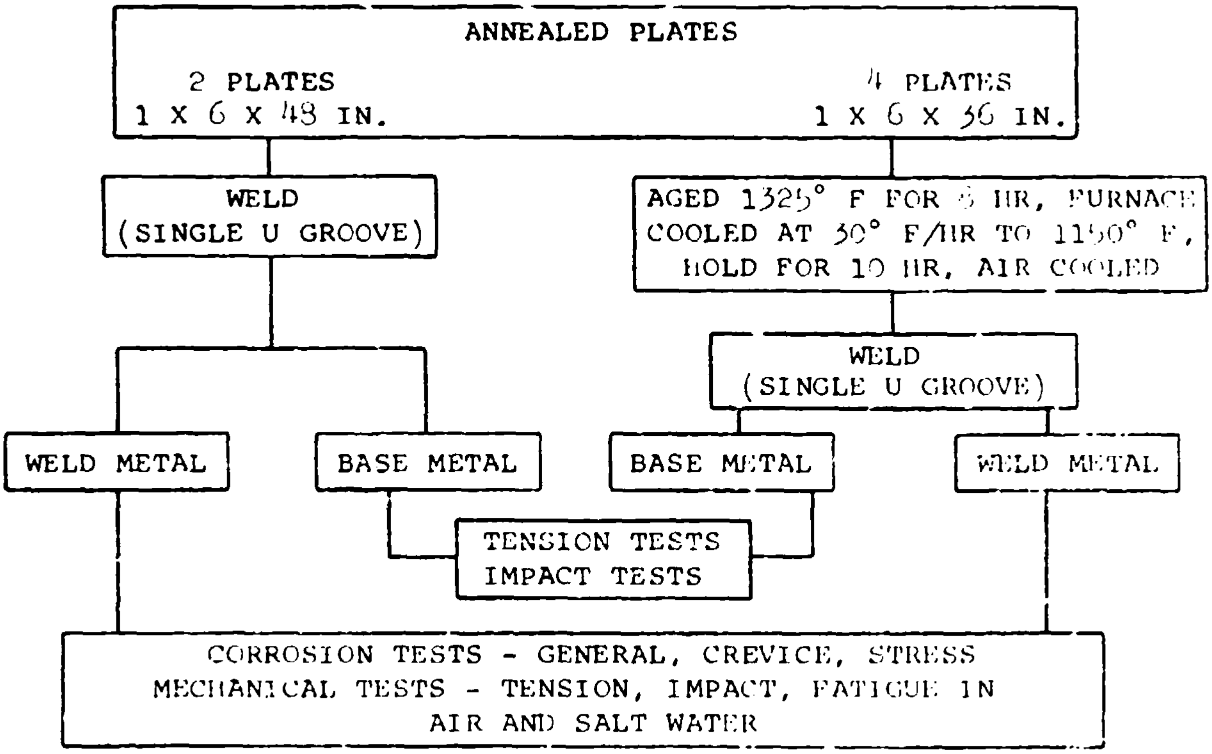
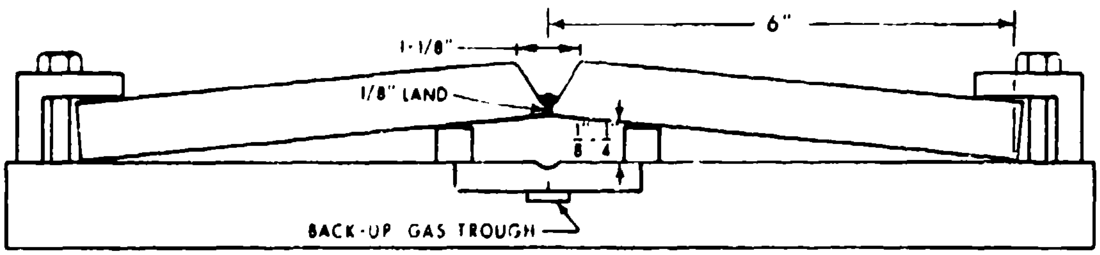


Figure 3
Welding and Heat Treatments
Inconel 718

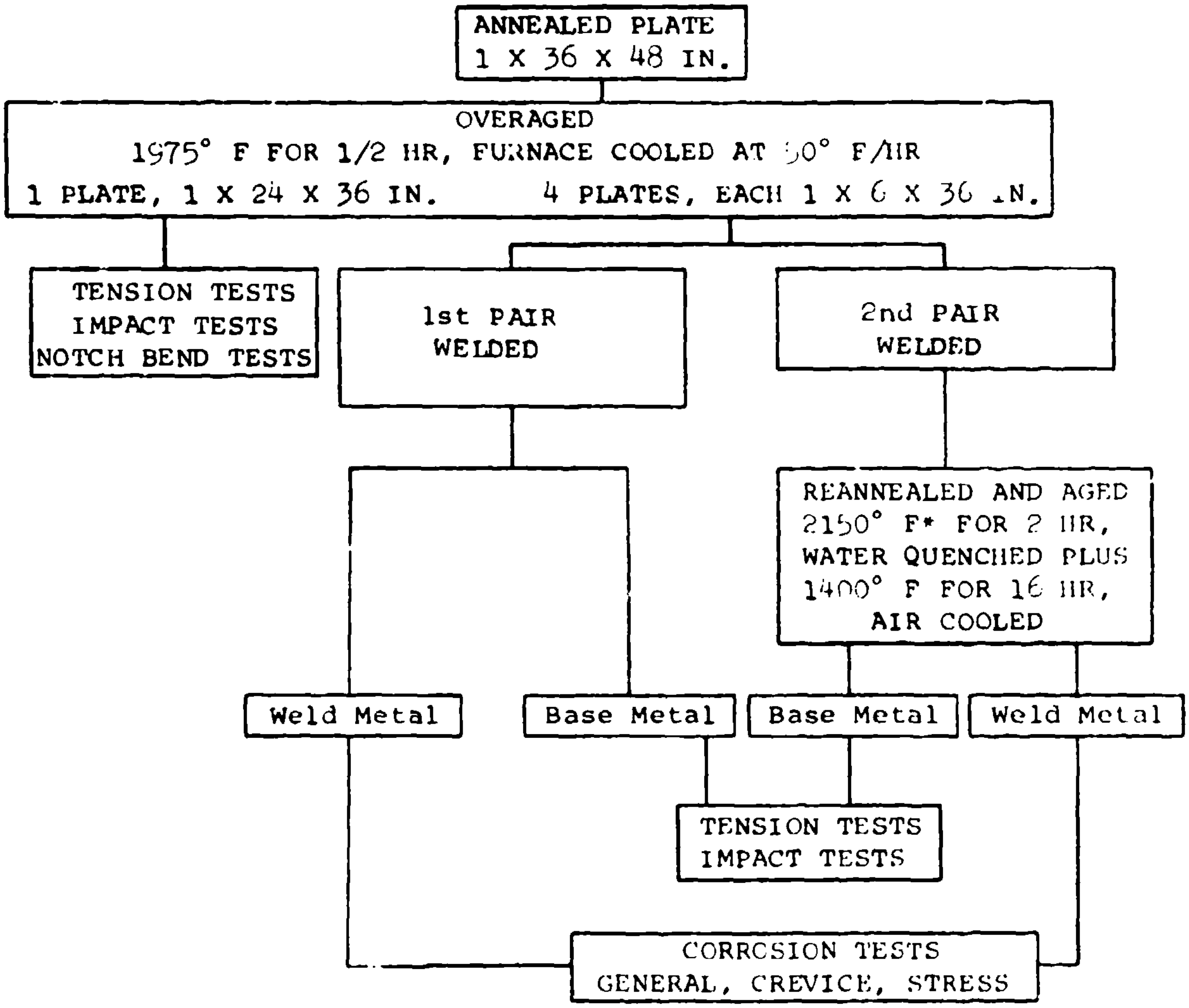
4528

Arc Voltage - 1[illegible]
Arc Current, amperes - 1[illegible]-[illegible]
Travel Speed, in/min - 1[illegible]
Wire Feed, in/min - 30
Interpass Temperature, ° F - [illegible]00 Maximum
Gas, cu ft/hr
  Torch
    Helium - [illegible]
    Argon - 1[illegible]
  Trailing Shield
    Argon - [illegible]
  Back Shield
    Argon - [illegible]
No. of Passes
  [illegible]-Inch Weld - [illegible]
  [illegible]-Inch Welds - [illegible]



WELDING FIXTURE FOR " THICK PLATE

Figure 4
Welding Parameters
Inconel 718



*ARGON ATMOSPHERE

Figure 5
Welding and Heat Treaments
René 41

4528

Arc Voltage	- 13	Gas, cu ft/hr	
Arc Current, amperes	- 250-300	Argon	
Travel Speed, in/min	- 6	Torch	- 30
Wire Feed, in/min	- 20	Trailing Shield	- 50
Interpass Temperature, ° F	- 60-150	Back Shield	- 20

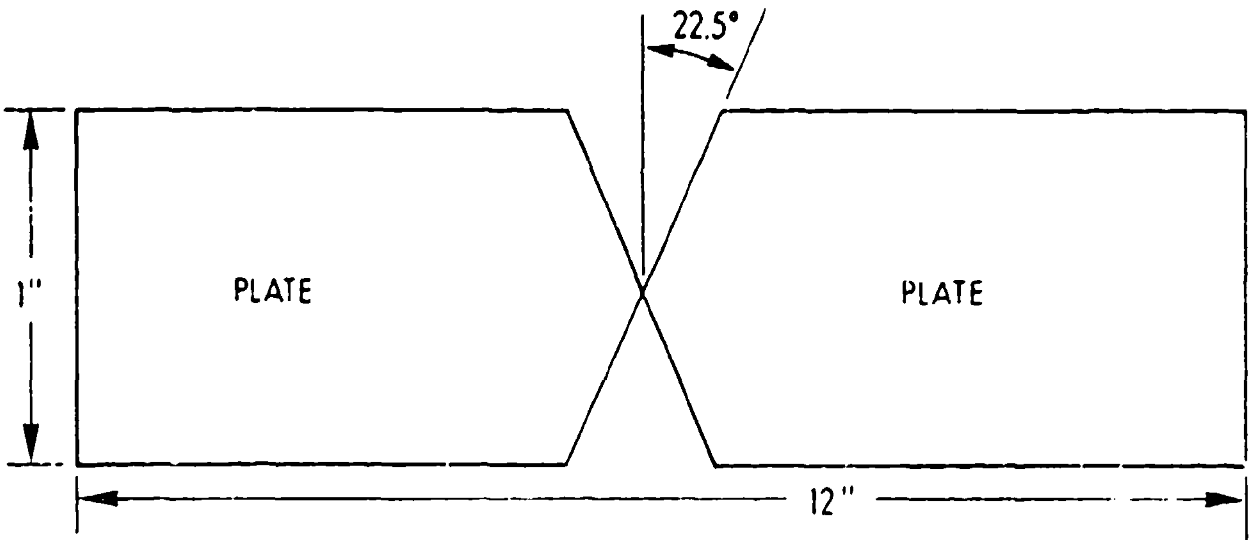


Figure 6
Welding Parameters
René 41

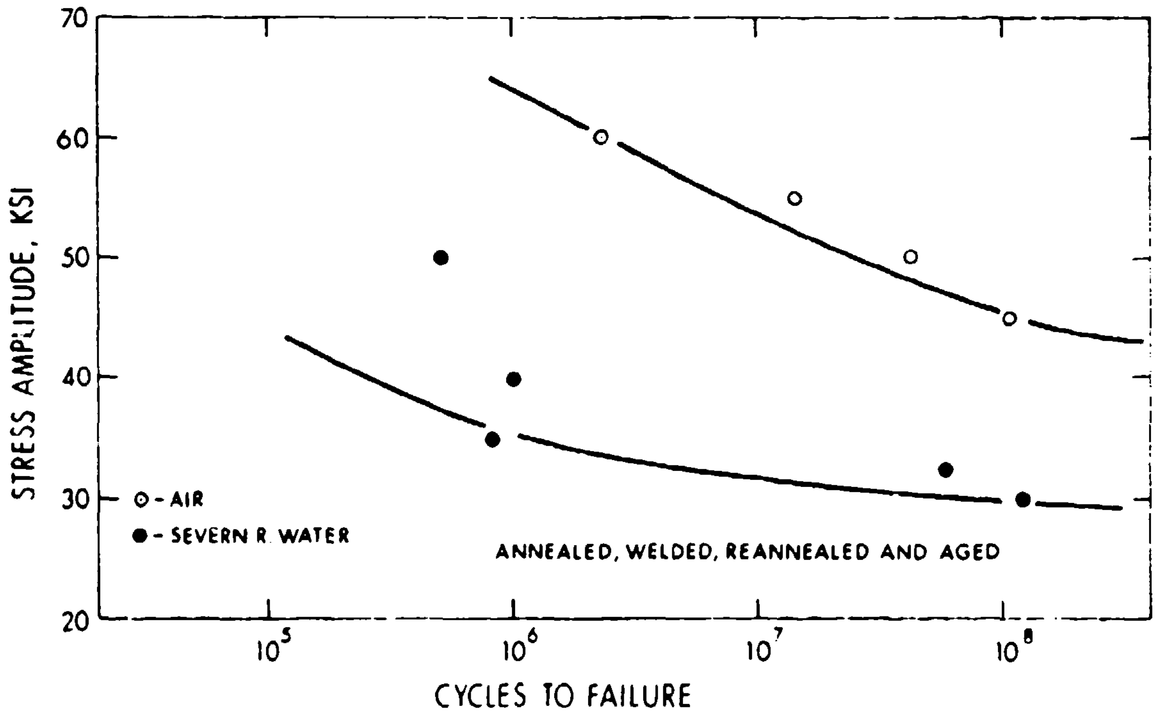


Figure 7
Fatigue Data
15-5 PH Stainless Steel

4528

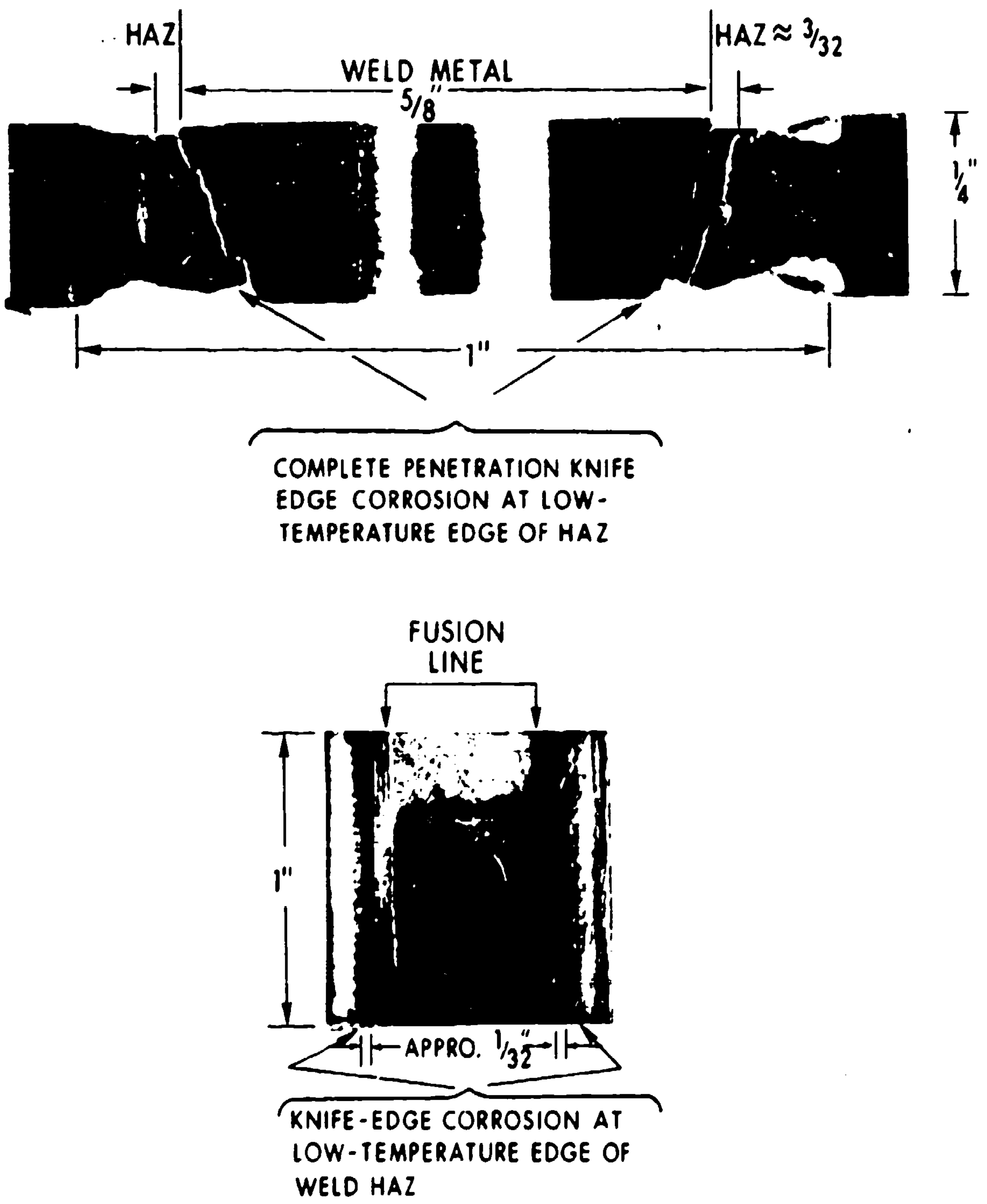


Figure 8
Knife-Edge HAZ Corrosion of As-Welded
15-5 PH Stainless Steel in Crevice Areas

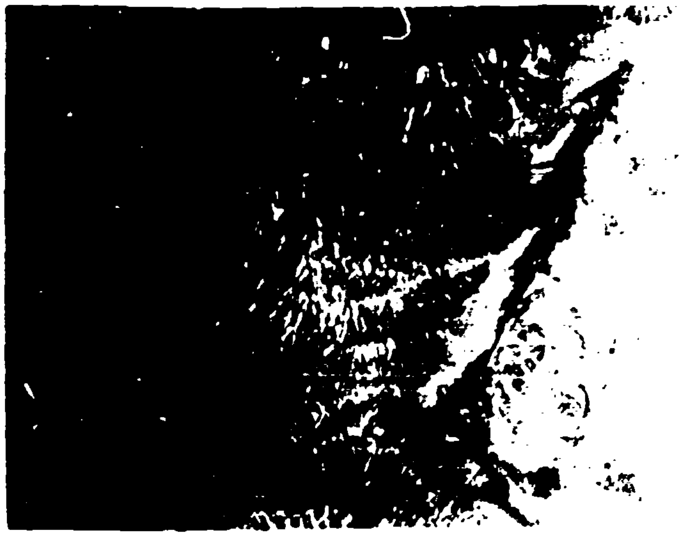


Figure 9
Knife-Edge HAZ Corrosion of
As-Welded 15-5 PH Stainless-Steel
SCC Specimen

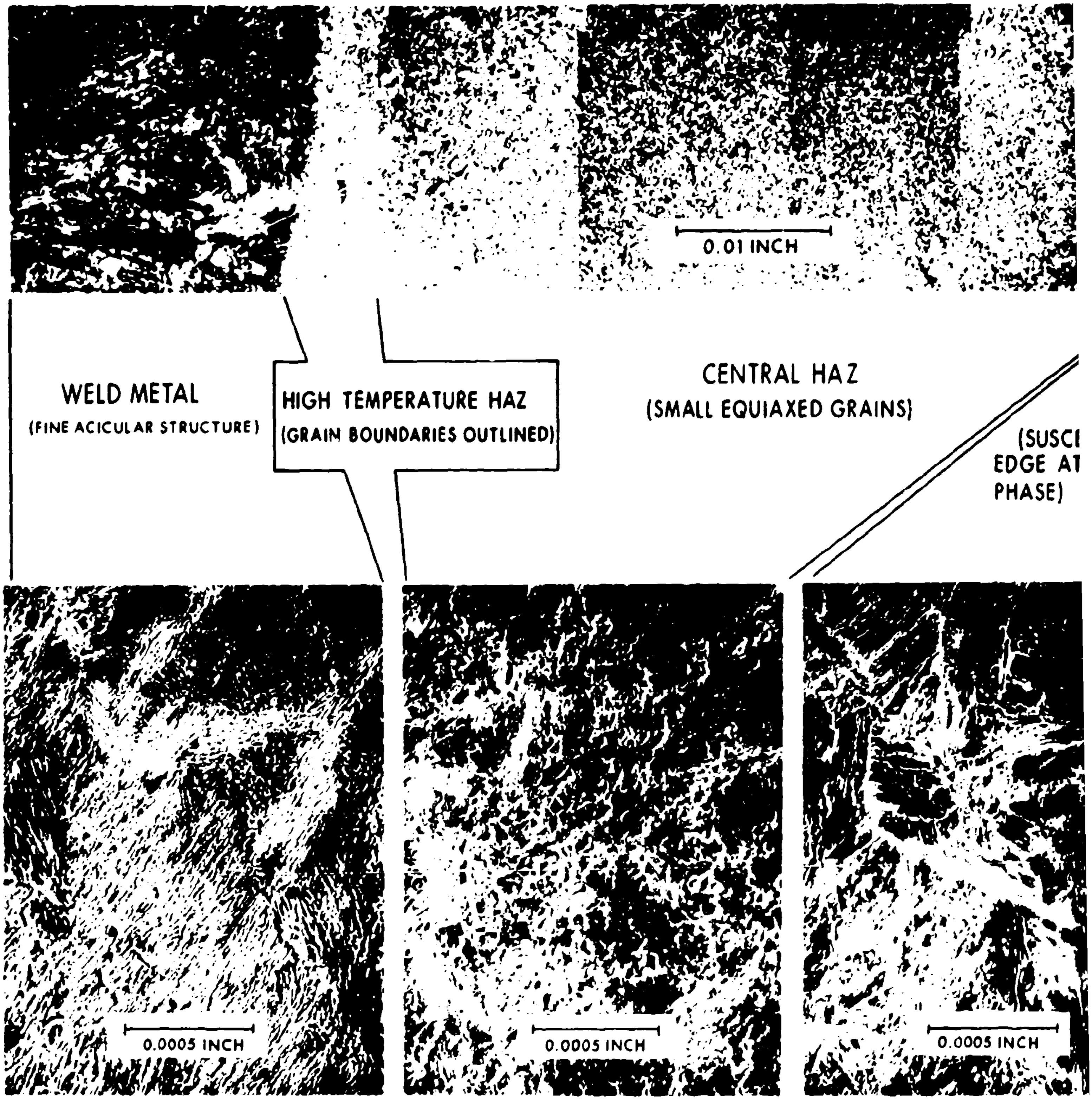
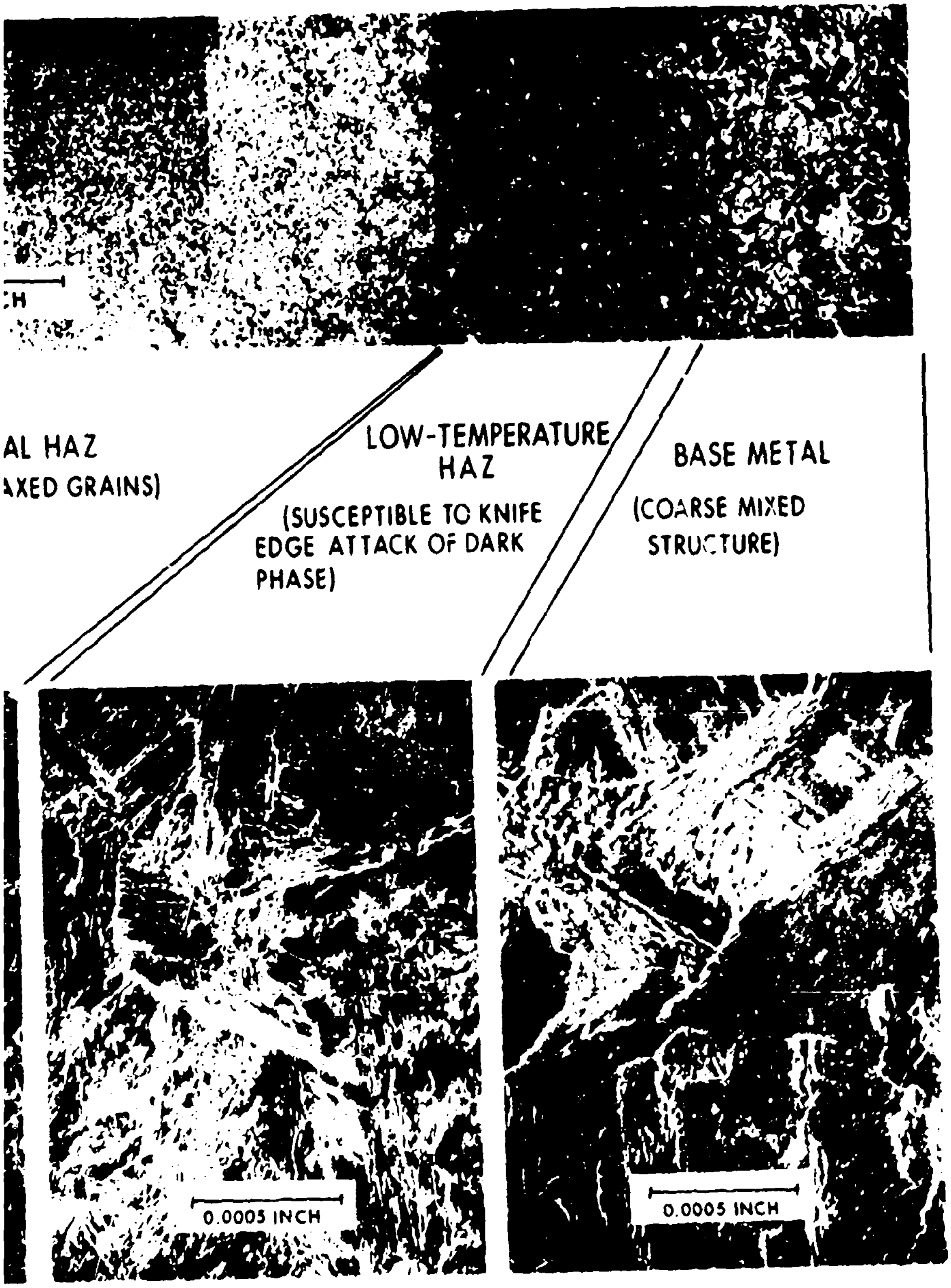


Figure 10
Metallurgical Structure of 15-5 PH
in the Weld HAZ (Fry's Reagent)

A-8


AL HAZ
AXED GRAINS)
LOW-TEMPERATURE HAZ
(SUSCEPTIBLE TO KNIFE EDGE ATTACK OF DARK PHASE)
BASE METAL
(COARSE MIXED STRUCTURE)
0.0005 INCH
0.0005 INCH

15-5 PH
agent)

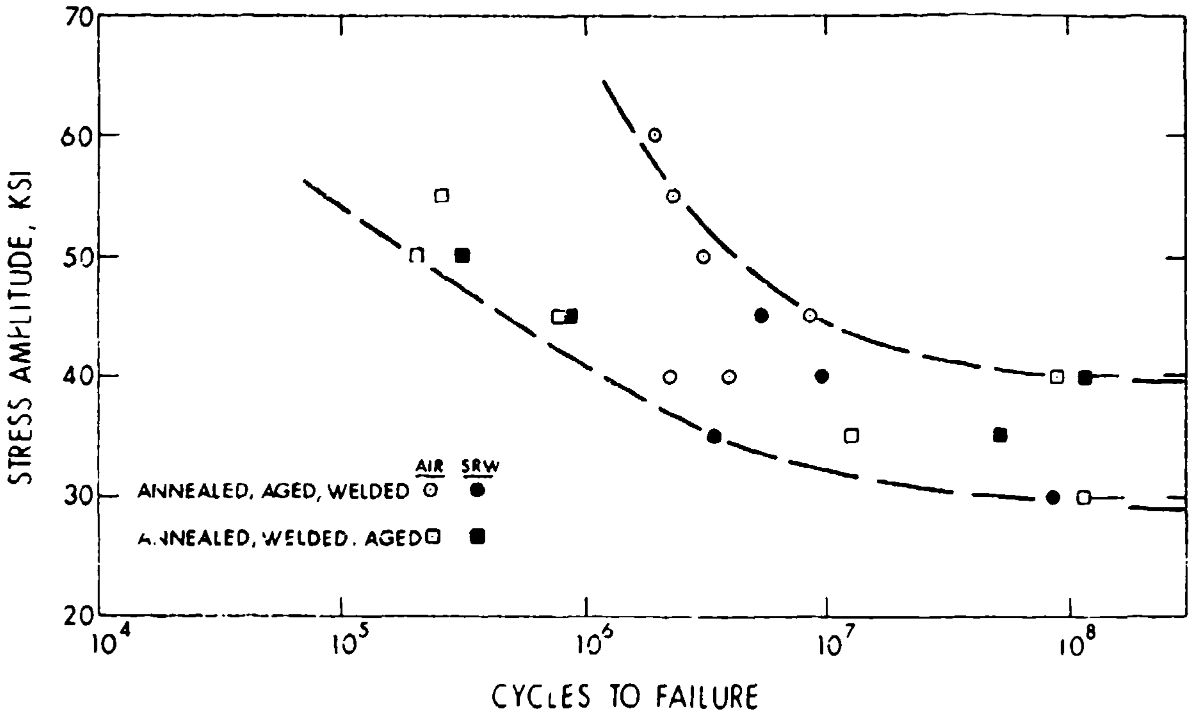


Figure 11
Fatigue Data Inconel 718

4528

APPENDIX A
WELDING OF RENÉ 41

Welding of René 41 in 1-inch thick section sizes had not previously been attempted. Any efforts in this direction were therefore of an experimental nature. For these tests, 2 pairs of plates were to be welded.

PROCEDURE

The first pair of René 41 plates were originally welded in a single "U" groove weld joint configuration. Root passes were made manually with Hastelly W filler wire and subsequent passes were made automatically with René 41 filler wire. The resulting weld appeared sound, with no evidence of cracking or porosity. X-ray inspection indicated no trace of cracking, lack of fusion, or porosity. Despite all efforts at mechanical restraint, the plates began to distort and bow upwards during welding due to shrinkage as the weld metal solidified. The resultant plate was bowed 15 to 20 degrees and was unsuitable for obtaining specimens.

This plate was subsequently cut apart and a double "V" groove weld joint machined on what had been the outside edges. The second pair of plates also had a double "V" groove machined in them. This double "V" joint appears in figure 1-A. Since the weld root was now in the mid-thickness of the plate, and because root cracking on the first (distorted) weld was absent, it was decided to use René 41 instead of Hastelloy W for the root passes. The balanced heat inputs (welding alternately above and below the root) inherent in the use of the double "V" groove weld joint essentially eliminated the plate distortion.

Welding was performed with an automatic GTA apparatus. The location of passes on the two final welds appear in figure 1-A. The plates in the upper drawing were welded with a small root gap while those in the lower drawing were butted together. The mismatch between the lower plates was 1/8 to 1/4-inch. In each weld, after the root passes were placed on one side, the plates were back-ground to eliminate root cracking where penetration of the weld metal was difficult. Dye-penetrant inspection was performed after grinding to ensure complete removal of any cracks. Welding was then completed, alternating sides after each group of several passes to minimize distortion.

Dye-penetrant and radiographic inspections were performed after welding. While one weld showed no indications of cracks, X-rays of the other indicated about 6 inches of cracking in the root.

In spite of precautions, all specimens taken from both welds showed evidence of cracking in the root area where weld metal had not penetrated. The lower plate in figure 1-A, tested as-welded, showed more severe indications, with unfused sections of base plate as wide as 1/8 inch.

DISCUSSION

Adequate welds could not be made on René 41 material. This was due to the undetected flaw caused by incorrect welding procedure. After the first weld passes, insufficient back-grinding of the land was performed, causing a root crack to be present during subsequent passes.

Figure 2-A presents macrophotographs of the René 41 welds. The upper photograph shows the almost complete penetration of the first pair of plates while the lower shows the gross base plate mismatch and lack of penetration of the second pair of plates. The angle of the crack was measured to be 22.5 degrees from the vertical, as expected from weld joint geometry. Figure 3-A shows microphotographs of both plates which reveal this same crack, even in the better weld. Notice that the cracks are perfectly straight, whereas HAZ cracking or microfissuring is expected to be intergranular.

Also the crack stops in the first weld bead, indicating no root cracking problems in the welded material. The absence of microfissuring indicates the effectiveness of overaging René 41 base plate before welding to produce a sound weld root.

The inability of the first dye-penetrant inspection to reveal the extensive root crack is probably due to folding over and masking of the crack when the root was ground. This problem might be solved by using carbon-arc gouging instead of grinding or by increasing the root gap so that the plates will not pull together during the first pass.

31<

The fact that no strain-age cracking or microfissuring occurred indicates the effectiveness of postweld annealing in an inert atmosphere and of welding overaged base plate in controlling these problems. The problem encountered would appear to be one of welding procedure rather than a lack of weldability of the material. This difficulty does, however, indicate a need for welding research and development before the material is available for strut and foil applications.

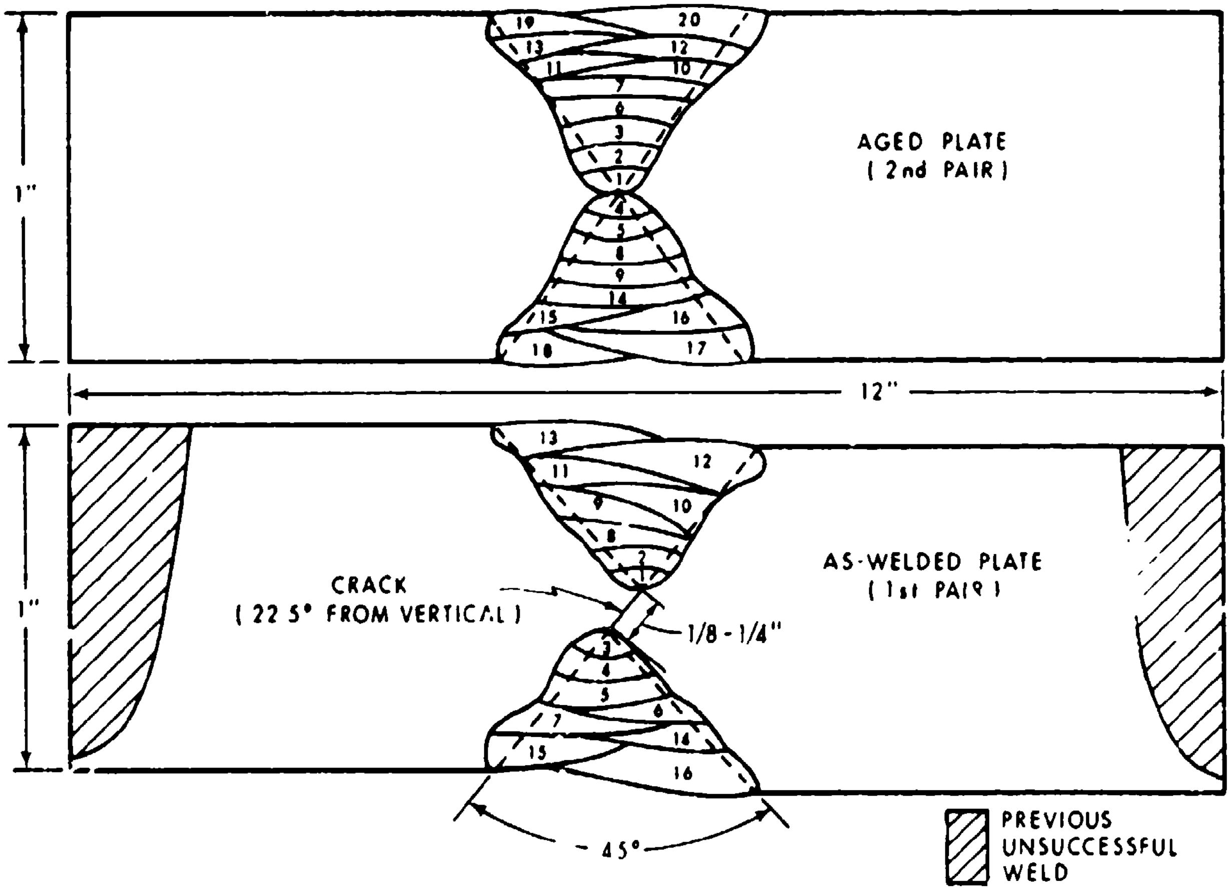


Figure 1-A
Weld Joint Details
René 41

4528

Aged Plate - Center

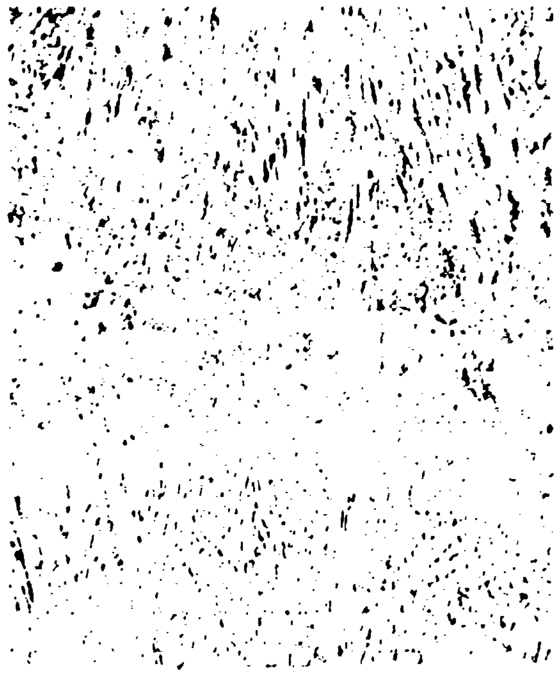
As-Welded Plate

Figure 2-A
René 41 Welds (4X)

4928

Aged Plate - End

Aged Plate - Center



As-Welded Plate
End of Crack

Figure 3-A
Rene 41 Weld Cracking (50X)